The impact hazard from small asteroids: current problems and open questions

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Abstract

The current philosophy of impact hazard considers negligible the danger from small asteroids. However, several facts claim for a revision of this philosophy. In this paper, some of these facts are discussed.

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1 Introduction

The interest in impact of interplanetary bodies with planets, particularly with Earth, has increased significantly during last years, because of several events, such as the fall of the D/Shoemaker–Levy 9 into Jupiter's atmosphere. At the dawn of the XXI century, in the internet era, the main forum of discussion is the mailing list *Cambridge Conference Net*, moderated very well by Benny Peiser. This lively debate was strengthened by the recent *IMPACT Workshop* held in Torino (Italy) on June 1–4, 1999, during which the impact hazard was widely discussed in all its sides.

Particular attention was given to the detection of kilometre–sized objects, which pose a severe threat to the Earth. During last years, this was already emphasized by several authors even though with different arguments (e.g. Aduskhin and Nemtchinov 1994, Chapman and Morrison 1994, Toon et al.

1997). The reason is quite simple: an impact of such an object can cause an extinction level event. The consequent "asteroidal winter", deriving from a strong injection of dust in the atmosphere, is quite similar to the nuclear winter except for radioactive consequences. It would cause the onset of environmental conditions whose main features are: a very long period of darkness and reduced global temperature. Something similar to the polar winter, but extended all over the world (Cockell and Stokes 1999).

Even though I understand and respect this opinion, I think that it is worth noting that we cannot neglect small bodies. This is the "juice" of my talk during the IMPACT workshop, of my recent intervention in the Cambridge Conference Network, of this paper.

2 Tunguska–like events

Small objects, of the order of tens or hundreds of metres, can cause severe local damages. The better known event in this range is the Tunguska event of 30 June 1908, whose effects are the devastation of an area of 2150 ± 25 km^2 and the destruction of more than 60 million of trees (for a review see Vasilyev 1998). Still today there is a wide debate all over the world about the nature of the cosmic body which caused that disaster. Just on last July an Italian scientific expedition, *Tunguska99*, went in Siberia to collect data and samples. First results will be presented during the 31st Annual Meeting of the Division for Planetary Science of the American Astronomical Society, but some general informations are available on the web at http://www-th.bo.infn.it/tunguska/.

Chapman and Morrison (1994) considered Tunguska–like events as a negligible threat. They might have reason, owing to large uncertainties in these studies, but they underestimated some values: first of all, the value of destroyed area in Tunguska, that Chapman and Morrison considered about 1000 km^2, while the *measured* value is more than twice (see above; Vasilyev 1998). The area of 1000 km^2 is about that where the peak overpressure would reach the value of 4 psi (27560 Pa), sufficient to destroy normal buildings. But it is worth noting that an overpressure of 2 psi produces wind of 30 m/s, which are sufficient to cause severe damages to wood structures. In addition to this, debris flying at such speed are a life hazard (Toon et al. 1997). Therefore, a reasonable value of human being at risk of life during a Tunguska–like event is 10^4, rather than 7×10^3 as indicated by Chapman and

Morrison (1994). The above value has been calculated by using the formula in Adushkin and Nemtchinov (1994) and assuming an explosion energy of 12.5 Mton (Ben–Menahem 1975).

Chapman and Morrison (1994) correctly noted that there are many more probabilities that such an event might occur in a uninhabitated part of the world. On the other hand, even though with scarce probabilities, it might occur on a well populated city and in that case the disaster will be great. For example, Rome has a population density of about 2000 people per square kilometre and then the human being at risk of life are more than 2 millions. Are 2 millions people or more a "negligible detail"? What about New York or Moscow or another overpeopled metropolis?

In addition to this, it is necessary to evaluate the impact frequency of Tunguska–like events. Chapman and Morrison considered a time interval of 250 yr, but several other studies and episodes suggested a lower value. Farinella and Menichella (1998) studied the interplanetary dynamics of Tunguska–sized bodies by means of a numerical model and they found that the impact frequency is 1 per 100 yr. However, in that study, authors did not take into account for the Yarkovsky effect (see Farinella and Vokrouhlickỳ, 1999, and references therein), that can slightly increase the delivery of NEO (Near Earth Objects) toward the Earth.

There are also ground–based and space–based observations that support these conclusions, even though the frequency range can vary very much. For a 1 Mton explosion, the impact frequency can be once in 17 (ReVelle 1997) or 40 yr (Nemtchinov et al. 1997b), that implies a Tunguska event (12.5 Mton) once in 100 or 366 yr. If we consider an energy of 10 Mton, as calculated by Hunt et al. (1960), we obtain a value of the impact frequency respectively of 88 or 302 yr. In addition to this, Steel (1995) reported two other Tunguska–like event in South America in 1930 and 1935: this strengthen the impact frequency value of one per 100 yr (or less).

Now, if we consider a typical time interval of one Tunguska–like impact per 100 yr and 10^4 deaths per impact, we obtain 100 world death per years, that is a value no more negligible in the Chapman and Morrison's scale (1994). *On the other hand, we would stress the large uncertainty of these values, mainly owing to the use of empirical relations with scarce data.*

The purpose of this paper is to propose a change in the philosophy of impact hazard and to consider also Tunguska–like events as dangerous. We are aware that the threat posed by kilometre and multikilometre objects is more dangerous and therefore we must study these objects and methods to avoid an extinction level event. However, these few data exposed in this paper suggest that we must *also* study Tunguska–like events, because they are dangerous and they provide useful data for calibration of theories.

3 The failure of current theories

The calculations of the impact hazard are strongly related with available numerical models for the fragmentation of asteroids/comets in the Earth's atmosphere. Actual models consider that the fragmentation begin when the dynamical pressure in front of the cosmic body is equal to the material mechanical strength. However, from observations of very bright bolides, it results the large meteoroids or small asteroids breakup at dynamical pressures lower than their mechanical strength. Still today there is no explanation available for this conundrum. This is of paramount importance, because it allow to know whether or not an asteroid might reach the soil. In addition to this, the atmospheric breakup has also effects on the crater field formation (Passey and Melosh 1980) or on the area devastated by the airblast. Therefore, it allows to establish a reliable criterium to assess the impact hazard. All studies showed above are based on models where the fragmentation begin when the dynamical pressure is equal to the mechanical strength of the asteroid. But, as we shall see, observations indicate that this is not true.

The interaction of a cosmic body in the Earth's atmosphere can be divided into two parts, according to the body dimensions. For millimetre to metre sized bodies (meteoroids), the most useful theoretical model is the gross–fragmentation model developed by Ceplecha et al. (1993) and Ceplecha (1999). In this model, there are two basic fragmentation phenomena: the *continuous fragmentation*, which is the main process of the meteoroid ablation, and the *sudden fragmentation* or the discrete fragmentation at a certain point.

Instead, for small asteroids another model is used, where the ablation is contained in form of explosive fragmentation, while at high atmospheric heights it is considered negligible. Several models were set up: Baldwin and Shaeffer (1971), Grigoryan (1979), Chyba et al. (1993), Hills and Goda (1993), Lyne et al. (1996). A comparative study on models by Grigoryan, Hills and Goda, and Chyba–Thomas-Zahnle was carried out by Bronshten (1995). He noted that the model proposed by Chyba et al. does not take into account the fragmentation: therefore, the destruction heights are over-estimated (about 10–12 km). Bronshten concluded also that the models by Grigoryan and Hills–Goda are equivalent.

There are also a class of numerical models, called "hydrocodes" (e.g., CTH, SPH), which were used particularly for the recent impact of Shoemaker–Levy 9 with Jupiter. Specifically, Crawford (1997) uses CTH to simulate the impact, while M. Warren, J. Salmon, M. Davies and P. Goda used SPH. The latter was published only on the internet and now is no more available.

Despite of particular features of each model, the fragmentation is always considered to start when the dynamical pressure p_0 in the front of the meteoroid (stagnation point) exceeds the mechanical strength S of the body.

Although direct observations for asteroid impact are not available, it is possible to compare these models with observations of bodies with dimensions of several metres or tens of metres. Indeed, in this range, the gross–fragmentation model overlaps the explosive fragmentation models. As underlined several times by Ceplecha (1994, 1995, 1996b), observations clearly show that meteoroids breakup at dynamical pressures lower (10 times and more) than their mechanical strength. These data are obtained from observation of photographic meteors and the application of the gross–fragmentation model, that can reach a very good precision. According to Ceplecha et al. (1993) it is possible to distinguish five strength categories with an average dynamical pressure of fragmentation (Tab. 1).

Table 1: Meteoroids category strength. After Ceplecha et al. (1993)

Category	Range of $p_{\rm fr}$ [MPa]	Average $p_{\rm fr}$ [MPa]
a	$p < 0.14$	0.08
b	$0.14 \leq p < 0.39$	0.25
c	$0.39 \leq p < 0.67$	0.53
d	$0.67 \leq p < 0.97$	0.80
e	$0.97 \leq p < 1.2$	1.10

Also for continuous fragmentation the results obtained indicate that the maximum dynamical pressure is below 1.2 MPa, but with five exceptions found: 4 bolides reached 1.5 MPa and one survived up to 5 MPa (Ceplecha et al. 1993).

It is also very important to relate the ablation coefficient σ with the fragmentation pressure $p_{\rm fr}$, in order to search for a relationship between the meteoroid composition and its ability to bear the air flow. To our knowledge, a detailed statistical analysis on this subject does not exist, but in the paper by Ceplecha et al. (1993) we can found a plot made by considering data on 30 bolides (we refer to Fig. 12 in that paper). We note that stony bodies (type I) have a wide range of values of $p_{\rm fr}$. Concerning weak bodies, we can see that there is only one cometary bolide (type IIIA), but this is due to two reasons: first, cometary bodies undergo to continuous fragmentation, rather than a discrete breakup at certain points. Therefore, it is not proper to speak about the fragmentation pressure; we should use the maximum tolerable pressure. The second reason is that there is a selection effect. Indeed, from statistical studies, Ceplecha et al. (1997) found that a large part of bodies in the size range from 2 to 15 m are weak cometary bodies.

However, a recent paper has shown that statistics from physical properties can lead to different results when compared with statistics from orbital evolution (Foschini et al. 1999). Specifically, it results from physical parameters, as indicated above, that a large part of near Earth small objects are weak cometary bodies, while, from the analysis of the orbital evolution, it results a strong asteroidal component.

The reason of the presence of cosmic bodies with very low fragmentation pressure can be explained with the assumption that additional flaws and cracks may be created by collisions in space, even though they do not completely destroy the cosmic body (Baldwin and Shaeffer 1971). Other explanations can be that the asteroid was not homogeneous (see the referee's comment in Ceplecha et al. 1996) or it had internal voids (Foschini 1998b).

These are hypoteses, interesting hypoteses, but none is conclusive.

4 Special cases

In addition to data published in the paper by Ceplecha et al. (1993) and Ceplecha (1994) we consider some specific cases of bright bolides. We provide here a short description and we refer for details to cited papers.

The Lost City meteorite (January 3, 1970), a chondrite (H), was analysed by several authors (McCrosky et al. 1971, ReVelle 1979, Ceplecha 1996a). The recent work by Ceplecha (1996a) is of particular interest, because by taking into account the meteoroid rotation, he succeeded in explaining the atmospheric motion without discrepancies. Obviously, except for the dynamical pressure, that in this episode reach the value of $p_{\rm fr} = 1.5$ MPa, while the mechanical strength of a stony body is about 50 MPa.

Table 2: Special episodes.

Name	Date	max $p_{\rm fr}$ [MPa]	S [MPa]
Přìbram	Apr 7, 1959	9.2	50
Lost City	Jan 3, 1970	1.5	50
Šumava	Dec 4, 1974	0.14	1
Innisfree	Feb 6, 1977	1.8	10
Space based obs.	Apr 15, 1988	2.0	50
Space based obs.	Oct 1, 1990	1.5	50
Benešov	May 7, 1991	0.5	10
Peekskill	Oct 9, 1992	1.0	30
Marshall Isl.	Feb 1, 1994	15	200

In the work by ReVelle (1979), it is possible to find also useful data for two other episodes: Přìbram (April 7, 1959) and Innisfree (February 6, 1977). In both episodes a meteorite was recovered: ordinary chondrite and L chondrite respectively. Values for $p_{\rm fr}$ of 9.2 MPa and 1.8 MPa respectively were obtained in this work.

The Šumava bolide (December 4, 1974) reached -21.5 absolute visual magnitude and was produced by a cometary body. It exhibited several flares during a continuous fragmentation, before to end at about 60 km heigth. The maximum dynamical pressure was in the range $0.025 - 0.14$ MPa, very much lower than the mechanical strength of a cometary body, i.e. 1 MPa (Borovička and Spurný 1996).

The Benešov bolide (May 7, 1991) was very strange and was analysed in detail by Borovička and Spurný (1996) and Borovička et al. (1998a, b). From these studies, it results that it was very probably a stony object which undergo a first fragmentation at high altitudes ($50 - 60$ km) at dynamical pressures of about $0.1 - 0.5$ MPa. However, some compact fragments were disrupted at pressures of 9 MPa (24 km of height).

The fall of the Peekskill meteorite (October 9, 1992) was the first of such events to be recorded by a video camera (Ceplecha et al. 1996). The fireball was brighter than the full moon and 12.4 kg of ordinary chondrite (H6 monomict breccia) were recovered. Tha availability of a video record allow to compute, with relative precision, the evolution of the meteoroid speed and, therefore, of the dynamical pressure. It was found that the maximum value of $p_{\rm fr}$ was about $0.7-1.0$ MPa, while the meteorite has an estimated strength close to 30 MPa.

During last years, space–based infrared sensors detected several bolides all around the world. Nemtchinov et al. (1997) investigated these events by using a radiative–hydrodynamical numerical code. They simulated three bright bolides (April 15, 1988; October 1, 1990; February 1, 1994) and they obtained respectively these results: stony meteoroid, $p_{\mathrm{fr}} = 1.6 - 2.0$ MPa; stony meteoroid, $p_{\mathrm{fr}} = 1.5$ MPa; iron meteoroid, $p_{\mathrm{fr}} = 10 - 15$ MPa. Concerning the latter event, Tagliaferri et al. (1995) reached a slightly different conclusion: stony meteoroid, $p_{\mathrm{fr}} = 9$ MPa.

The condition that the fragmentation starts when the dynamical pressure reaches the mechanical strength of the meteoroid was imposed by Baldwin and Shaeffer (1971), but it is worth noting that it is a hypotesis. Now we have sufficient, even though not complete, data to claim that this hypotesis has no physical ground and we have to search for new conditions for fragmentation.

5 Conclusion

The current philosophy of the impact hazard from small bodies need a revision and, in this paper, are discussed sufficient data and arguments to support such a revision. Specifically, we need for a theory consistent with observations. Today, the leading group in this field is surely that of Nemchinov in Moscow, in cooperation with Sandia National Laboratories. They are developing a numerical model of the hypersonic flow around the cosmic body, with the inclusion of ablation products.

However, another approach, based on plasma physics, is rising (Foschini 1999). It is worth noting that the plasma approach is at its very beginning and, therefore, there are only some new ideas supported by calculations of orders of magnitude. However, this approach has thrown a new light on some aspects of meteor physics, such as the electrophonic sounds (Beech and Foschini 1999), electromagnetic interferences in hypervelocity impacts (Foschini 1998a), the interaction of radio waves with meteoric plasma (Foschini 1999).

However, today we can only say that current models of fragmentation of small asteroids in the Earth's atmosphere *are not consistent* with observations.

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